

# **The Comet and Asteroid Impact Hazard in Perspective**

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## Abstract

The potential hazard from comet and asteroid impacts is one of a number of serious natural and man-made calamities facing modern society. However, only three of these have the potential to wipe out a significant fraction of human life on this planet: impacts, nuclear war, and the AIDS epidemic. How urgent then is it that action be taken at this time to mitigate the possibly catastrophic effects of impacts, and what fraction of available resources should be given over to this problem? By at least two measures commonly used to estimate the seriousness of potential threats, frequency of occurrence and annual fatality rate, impacts do not demand priority attention from society at this time. In addition, the current credibility of the impact hazard with the public and with government decision makers is likely too poor at this time to support a drive for major expenditures on defensive systems. A program of public education, and ongoing research is recommended to gain public support, to better establish the nature of the impact hazard, and to provide a database for eventual mitigation development. Waiting a decade or more to begin work on a defensive system subjects society to minimal risk, while allowing emerging technologies to develop which may sharply reduce the cost and/or complexity of such a defense.

## Introduction

To present-day astronomers, the concept of comets and asteroids striking the Earth with catastrophic consequences, is obvious. The surfaces of the terrestrial planets and the Moon, as well as the satellites of the giant planets, bear testimony to the violent early bombardment history of the solar system. Age dating of craters on the Earth shows that this is an ongoing process, and the presence of comets and asteroids in Earth-crossing orbits allow calculation of the probability of random impacts by this population of objects (Weissman 1990; Shoemaker et al. 1990).

To the general public, however, the threat of cataclysmic meteorite impacts seems a remote one. There is no known incident of a major crater-forming impact in recorded human history. The only documented airburst event is the 1908 Tunguska event, and even that event is much less widely known to the general public than similar terrestrial catastrophes such as the 1883 Krakatoa volcanic eruption, which was of comparable magnitude. Lesser events such as the Sikhote-Alin meteorite fall in 1947 (Krinov 1963) or the October, 1992 (di Cicco 1993) fall of a 27 pound meteorite in Peekskill, New York, which destroyed a Chevy Malibu sedan, are looked upon as curiosities, but not generally as harbingers of a much worse catastrophe.

There are thus two aspects to the comet and asteroid hazard problem. First, how can astronomers best describe the impact hazard problem to the general public and to decision makers in government, so as to establish the genuine nature of the hazard and maintain credibility, while not creating undue alarm? Second, what weight should be given to the problem and what resources diverted to meet it, in the light of numerous other hazards encountered by society in an already imperfect world?

These questions deal with subjects which go far beyond the normal scientific questions

that we as astronomers are asked to consider. They involve economic, social, political, and moral issues, as well as scientific and technological ones. This researcher can not claim to be an expert in all those areas. However, the organizers of the meeting have asked the author to provide such a discussion with particular attention to the question of whether a technology program to develop an active impactor defense should be begun in the near future.

The discussion that follows should thus be looked upon as one by an informed citizen and generalist, and not a specialist and expert in each of the many disciplines involved. The discussion will be technical, but will also involve opinions and judgments which are solely those of this researcher; wherever possible, those opinions and judgments will be clearly identified as such. In bringing the comet and asteroid hazard problem to the fore, it is our responsibility as scientists to provide the best possible information in an unbiased manner, so that a full public discussion of the issues and informed decision making can take place.

In attempting to place the impact hazard problem in perspective, there are several major ways in which the problem can be considered. First, what is the **urgency** of the problem? How important is it that some action be taken now? What are the consequences of not taking action? Second, what is the **uncertainty** in our knowledge of the potential impactors? Do we know enough about their physical structure, population, and orbital dynamics to properly evaluate the hazard and to design mitigation technologies? Third, what is the **priority** of the problem? Are there other more immediate problems demanding attention and resources? Should the impact hazard take precedence over other hazards confronting society and the environment? Fourth, what is the current **credibility** of the impact hazard problem in the eyes of the public, of government officials, and of the media? Will requests for funding for increased telescopic searches, spacecraft missions to near-Earth objects, and study of mitigation technologies fall on

deaf ears, or worse yet, be greeted with derisive laughter?

In addition, is deflection of asteroids and comets **plausible** at this time with currently available or soon-to-be available technologies? Can deflection technologies be developed and tested **legally** at this time, or would they require renegotiation of existing international treaties? Can such technologies be tested **safely** so that they do not pose a risk to international stability, and so that they do not somehow, inadvertently, increase the impact hazard to the Earth? These questions will be discussed below.

### **Urgency of the Impact Hazard Problem**

The question of urgency is one that lends itself most readily to a scientific analysis. The current knowledge of Earth-crossing and Earth-approaching comet and asteroid orbits is sufficient to estimate impact probabilities and energies with a fairly high degree of accuracy. Estimates of the number of objects and their mass distributions, while still somewhat uncertain, particularly with regard to comets, is in rough agreement with the frequency of impacts observed from counted craters on dated surfaces (Grieve 1987). Thus, one can readily estimate the risks to society of waiting to take action on this problem.

For the sake of this discussion, assume that a rudimentary asteroid and comet deflection capability can be developed in a time period of 10 years. Also, assume that the applicable technology will be nuclear warheads on conventional rockets; this is the basic deflection system that has currently been proposed (non-nuclear explosives are also possible, but are likely do not have the necessary energy yield per unit mass). All of the major areas of technology required for such a mitigation defense are currently in hand. They include large launch vehicles (e. g., Titan IV, Proton, Shuttle, Energia), nuclear warheads up to 10 megatons (or more?) in explosive

yield, near-Earth object detection and tracking telescopes, and technologies for navigating a warhead to, and homing in on a specified target, There are many questions that still need to be answered in integrating the various technological elements into a functioning defense system, and many questions about how it should be used. Assume that the 10 year development program will answer all of those questions.

Ten years does not seem unreasonably long or short for such a program. Consider that the Manhattan Project produced not one, but two different, functional nuclear weapons within five years of the start of the program. The Apollo Program accomplished a manned landing on the Moon (and successful return) in just over eight years from the speech by President Kennedy initiating the program in 1961, In each of these cases, much of the required technology was not in hand at the start of the program, and numerous major design problems needed to be solved in the course of development. In comparison, integration of existing technologies into a rudimentary asteroid/comet defense seems a relatively easily obtainable, though likely expensive, goal.

What then is the risk to which society is exposed by not immediately developing a deflection defense against asteroids and comets at this time? Currently, no known object is on an Earth-impacting trajectory for the predictable future. What is the probability that existing searches will discover such a body next year? That probability is given by

$$p = 1 - (1 - p_i)^{N D} \approx p_i N D \quad (1)$$

where  $p_i$  is the mean probability of an impact,  $N$  is the number of years between discovery and impact to be considered, and  $D$  is the number of objects discovered per year.

Consider the Earth-crossing asteroids first. The mean probability of an impact is  $4.2 \times 10^9 \text{ yr}^{-1}$  (Shoemaker et al. 1990). Discovery rates ranged from 15 to  $50 \text{ yr}^{-1}$  between 1988 and

1992 (Morrison 1992); as a rough mean, a value of  $35 \text{ yr}^{-1}$  will be used here. Then, the probability of discovering an object next year that will impact within 10 years is

$$p = 1.5 \times 10^{-6} \times \frac{4.2}{P_i} \times \frac{10^{-9} \times 10}{N} \times \frac{35}{D} \quad (2)$$

a fairly small number.

One can further extend the calculation by asking what is the probability that an Earth--crossing asteroid will be discovered at any time in the next  $N$  years, with an impact occurring within those  $N$  years? Assuming the same numbers as above, but allowing discovery rates to grow 20% per year, and summing the probability over each of the next 10 years, the resulting value is:  $p = 1.5 \times 10^{-5}$ , still a rather small number.

Suppose then that all of the estimated 2,100 Earth-crossing asteroids with diameters  $> 1 \text{ km}$  (Shoemaker et al 1990) are discovered. What is the probability that one of them will impact within the next 10 years?

$$P_{\text{NEA}} = 8.8 \times 10^{-5} \times \frac{4.2}{P_i} \times \frac{10^{-9} \times 10}{N} \times \frac{2,100}{N_{\text{ast}}} \quad (3)$$

still a fairly low probability event. Note that this is the probability for an event anywhere on the Earth's surface, much of which is either ocean or sparsely populated land areas.

One can perform a similar calculation for smaller, Tunguska type events. For these locally destructive events, one can restrict the hazard estimate to airburst events over heavily populated areas. Consider that the annual probability of a Tunguska type event anywhere on the Earth is estimated to be  $4 \times 10^{-3}$  (Morrison 1992). Only 29% of the Earth's surface is land area, and much of that is uninhabited (Kurian 1989). In the United States, urban areas and transportation account for 2.9 % of land use; the world average is closer to 2% (Ehrlich and

Ehrlich 1989). Ninety-two per cent of the land in the United States is classified as pasture, rangeland, crops, **ungrazed** forest, desert, swamp, tundra, national parks, wildlife refuges, surface mining, and transmission lines (Ehrlich et al. 1977). Farm buildings account for 1.2% and military bases 1.3 %. To be conservative, assume that worldwide one would be concerned about airbursts over a land area twice that of the urban fraction in the United States, or 5.8%. Then the annual probability of a Tunguska type event over a populated area is  $6.7 \times 10^{-5}$ . The probability of a Tunguska event over a populated area occurring in the next 10 years is  $6.7 \times 10^{-4}$ .

Similar calculations can be performed for long and short-period comets. Weissman (1982) found a mean impact probability for long-period comets of  $2.2 \times 10^{-9}$  per perihelion passage (see also the chapter by Marsden and Steel in this volume), Weissman (1990) estimated that an average of 10.1 long-period comets brighter than absolute magnitude  $H_{10} = 11$  passed perihelion inside the Earth's orbit per year, based on Everhart's (1967) flux of long-period comets, corrected for observational selection effects, Using the cometary mass distribution found by Weissman (1990), this implies 57.2 Earth-crossing comets  $> 1$  km in diameter per year. Thus the probability of a long-period comet impact sometime in the next 10 years is

$$p_{LP} = 1.3 \times 10^{-6} \times \frac{2.2 \times 10^{-9} \times 10}{P_i} \times \frac{1}{N} \times \frac{57.2}{N_{LP-com}} \quad (4)$$

This is substantially less than the hazard posed by the Earth-crossing asteroids, even when one considers the higher mean impact velocities of the long-period comets,  $\sim 58$  km s $^{-1}$ . Substantially higher cometary fluxes are expected during "cometary showers" (Hills 1981) when large numbers of long-period comets are perturbed out of the Oort cloud by a close stellar passage or an encounter with a giant molecular cloud (Weissman 1990). However, current

evidence is that we are not experiencing a cometary shower, and the onset time for such a shower is  $\sim 10^4$  to  $10^5$  years, so they do not pose an immediate threat.

There are 25 short-period comets in Earth-crossing orbits listed in the most recent comet catalog (Marsden and Williams 1992). Of these, 4 are lost (their orbits are not well-determined and they have not been observed on recent returns), 1 disintegrated in 1853 (Comet Biela), and 1 is no longer Earth-crossing. Taking the 25 orbits as representative, the mean impact probability is  $6.4 \times 10^{-10} \text{ yr}^{-1}$  (Shoemaker et al., this volume). The estimated total number of active short-period comets larger than 1 km in diameter is 40 to 100 (Weissman 1990; see also chapter by Shoemaker et al. in this volume). Thus the probability of an impact in the next 10 years is given by

$$P_{SP} = 6.4 \times 10^{-7} \times \frac{6.4 \times 10^{-10}}{P_i} \times \frac{10}{N} \times \frac{100}{N_{SP-com}} . \quad (5)$$

One possible additional source of impactors not considered here is extinct short-period comets. It has been suggested that some fraction of the known Earth-crossing asteroids are short-period comet nuclei that have evolved to dormant, inactive states (Weissman et al. 1989). These objects are presumably already included in the estimated NEA population of 2,100 objects  $> 1$  km in diameter. However, there may additionally be a substantial number of extinct short-period comets in more typical Jupiter-crossing orbits, analogous to the active Jupiter and Halley family comets. Shoemaker et al. (this volume) argue that such objects may account for as much as an additional 25% in the total impact rate. That estimate is very uncertain because of the complex observational and dynamical selection effects involved, and because of assumptions as to whether the source of the short-period comets is the Oort cloud or the Kuiper belt. For the purposes of the discussion here, those objects will be ignored; although they may raise the total

impact rate by - 25%, that is not significant in the context presented herein.

The total impact hazard for all of the possible sources discussed above can be approximated by summing the individual probabilities. The result is a probability of  $7.6 \times 10^{-4}$  for an impact sometime in the next 10 years. That total is dominated, as one would expect, by the smallest, most frequent impactors, the locally destructive Tunguska airburst events. If one considers only impacts by objects  $> 1$  km in diameter, then the probability is  $0.9 \times 10^{-4}$  of such an impact in the next 10 years. That rate is dominated by near-Earth asteroids, and is in good agreement with estimates by Shoemaker et al. (1990).

The question then is whether these probabilities are sufficient motivation to justify action by government agencies, in particular development of a deflection capability. Governments regularly construct and/or promote defensive systems against natural disasters such as earthquakes, floods or storms, through mechanisms such as building codes, levees, warning and evacuation plans, etc. These defensive systems are typically scaled to deal with expected events that occur, within a factor of two, once in 100 years. For the impact hazard, the frequency with which events might occur is less than once in  $10^4$  years for Tunguska-like airbursts (over populated areas), and less than once in  $10^5$  years for major impacts (anywhere on Earth).

In addition, pragmatic and/or parochial disaster planners will note that the land area of any single nation is only a small fraction of the total target area of the Earth. The United States occupies 6.4% of the land area of the Earth, or only 1.9% of the total area. For Russia, the corresponding numbers are 11.5 % and 3.3%; for the member nations of the European Space Agency those numbers are 1.7 % and 0.5%. Since only currently space-faring nations are likely to be able to do anything about the impact hazard, will they commit resources to defending what will likely be someone's else's territory against these low probability events?

At some point, impacts become a global hazard because of climatic effects, and thus a major impact anywhere on the Earth will likely affect all nations. The threshold for globally catastrophic events is highly uncertain. Toon et al. (see chapter in this volume) put the threshold at an impact energy of  $10^5$  to  $10^6$  megatons, or an impactor diameter of 1 to 2.2 km (assuming an asteroid with a density of  $3.5 \text{ g cm}^{-3}$  and an impact velocity of  $20 \text{ km s}^{-1}$ ). Based on the estimates above, the probability of such an impact is  $0.9 \times 10^{-5} \text{ yr}^{-1}$  for the lower limit of the energy range, or about 5 times less for the upper limit.

This, of course, is the conundrum of the impact hazard. The probability of major impacts occurring on the Earth, or Tunguska airbursts over populated areas, is typically much lower than most natural or man-made disasters, but the possible lethal results maybe very much greater. How does one properly allocate resources to such rare but devastating events?

### **Uncertainty of the Impact Hazard**

As already noted, impact frequencies are fairly reliably known for both comets and asteroids, with the major uncertainty coming from estimates of the sizes of each population, and the mass distributions of the individual objects. Estimates are generally much better for asteroids than for comets. However, the cratering rate on the Earth and Moon obtained by counting craters on dated surfaces (Grieve 1987), serves as a direct check on those estimates and shows that they are correct to within a factor of two.

Considerably less is known about the physical nature of the individual impactors. Without such a database, it is difficult to develop precise models for how to deflect these objects. Of particular interest are the internal structure, bulk density and material strengths. Some of this information can be inferred from meteorite samples recovered on the Earth, but

the meteorites are a biased sample, both dynamically and compositionally, and likely do not contain any samples of cometary materials.

Current models of the internal structure of both asteroids and comets have tended to focus on what are known as rubble pile or fractal models (Davis et al. 1989; Weissman 1986; Dorm 1991). In the case of the asteroids it is suspected that many are reassembled fragments of larger objects, bound only by self-gravity, while for the comets the nuclei are believed to be weakly-bonded, primordial agglomerations of small icy planetesimals. Support for these models have come from radar observations of two near-Earth asteroids, 4769 Castalia and 4179 Toutatis, both of which appear to show bimodal structure (Ostro et al, 1990, 1993), and from observations of random and tidal disruption of cometary nuclei, most recently comet Shoemaker-Levy 9 which apparently disrupted during a pass within the Roche limit of Jupiter in 1992 (Marsden 1993). In addition, theoretical modeling of the effects of impacts on asteroidal bodies (Nolan et al, 1992) has suggested that the internal structure of many small asteroids could be highly fractured, even if they initially were single, unified bodies.

Additional uncertainty exists with regard to asteroid and comet regoliths. It had been expected that there would be very little regolith on small asteroids because of the inability of their weak gravitational fields to retain even low-velocity ejects. However, Galileo spacecraft visual and infrared imaging of asteroid 951 Gaspra (Belton et al, 1992; Weissman et al. 1992) has implied a substantial regolith on that asteroid's surface. The Galileo flyby of asteroid 243 Ida in August 1993 will provide additional data on this question, Little is known about cometary regoliths. It is expected that cometary nuclei cover themselves with a non-volatile lag deposit of large grains, but it is not known if this material is simply a loose agglomeration or a welded surface layer (Rickman, 1991).

The uncertainty about the internal structure of comets and asteroids, and the existence of regoliths on small asteroids, both create problems for deflecting these bodies by means of large explosions on their surfaces or nearby in space. Because of the regolith, coupling of the blast to the underlying “bedrock” (if there is a single, unit structure) may be highly inefficient. If the entire body is fragmented, in essence a continuous regolith, then coupling of the blast to the object may be extremely poor. A deflecting blast may instead result in fragmentation of the asteroid or comet nucleus, with little or no change in orbital parameters. Thus, instead of a single large object on an Earth-impacting trajectory, one may produce a “shotgun blast” of smaller impacts. It is entirely possible that the cumulative effect of those numerous smaller impacts may be much greater than a single impact by an equal mass object,

The Galileo flyby of Gaspra was not able to measure the asteroid’s mass, and hence its bulk density. Indirect estimates of asteroid masses of a few of the largest mainbelt objects have been made based on perturbations of other mainbelt asteroids during close approaches (Schubart and Matson 1979). These values have tended to confirm expectations of density based on spectroscopic type and meteorite analogs. However, the errors in such estimates are typically -10 to 50%, and no measurements have been made of the density of small asteroids, similar to the NEA’s.

Estimates of comet nuclei densities have also been performed indirectly based on fits to observed nongravitational forces (from jetting of surface volatiles) in the orbital motion of comets. Estimates for comet Halley range from 0.2 to 0.5 to 1.2 g cm<sup>-3</sup> (Rickman 1989; Sagdeev et al. 1987; Peale 1989), with error bars extending over the entire range of possibilities. Thus, for the moment, cometary bulk densities are essentially unknown.

In the case of near-Earth asteroids, UV photometry and visual and infrared spectroscopy

has allowed the identification of the surface compositions of some of the NEA's, and these have been matched to meteorite analogs, fragments of the NEA's recovered on the Earth's surface. However, the bulk composition of the individual asteroids is still unknown, though the Galileo measurements did show evidence for some compositional heterogeneity on Gaspra (Granahan et al. 1992). Although a great deal was learned about cometary composition from the Halley flyby missions in 1986 (Krankowsky 1991), there is still a great deal more that needs to be studied, in particular about the hydrocarbon component of the nucleus. The discovery that a substantial fraction of the nucleus mass was contained in pure hydrocarbon, or "CHON" (for "carbon-hydrogen-oxygen-nitrogen") particles was one of the major surprises of the Halley spacecraft missions. Also, there is evidence for chemical heterogeneity among the individual nucleus fragments (Mumma et al. 1993). These current unknowns concerning composition will introduce additional uncertainty in estimating the coupling between the deflecting blast and the object to be deflected.

To remove these uncertainties, a series of spacecraft missions are required to study the composition and physical structure of Earth-approaching comets and asteroids. These must be rendezvous missions so as to allow precise determinations of the mass and bulk density of the objects, as well as higher gravity harmonics which would be a clue to internal structure. The spacecraft must carry science instruments which will provide the elemental, molecular, and mineralogic compositions of each object. Internal structure should be probed using either microwave sounding techniques (likely possible for comets) or through direct seismic experiments. Rendezvous missions to multiple objects are required so as to examine compositional and structural diversity among these populations, and thus establish the range of parameters that could be expected in defending against an impact by any random object.

## Priority of the Impact Hazard

The hazard posed by impacts of comets and asteroids is not the only problem facing society. Currently identified ecological problems include overpopulation, global warming, global cooling and climate change (from volcanic aerosols), ozone depletion, and deforestation. Furthermore, there are human problems such as malnutrition, disease (in particular, but not only, AIDS), and pollution, and political problems such as nuclear proliferation and ethnic strife. Additionally, some areas of technical investigation, such as earthquake prediction, have substantial potential for preventing substantial loss of life and/or economic damage. These lists are not meant to be all-inclusive, but rather provide a sample of the global questions facing modern society.

All of these hazards place demands on governments for solutions, and for the resources to achieve those solutions. Many of the hazards are interrelated, in both positive and negative ways. For example, deforestation provides land for growing food and for allowing population growth. On the other hand, malnutrition and disease serve as a check on overpopulation, though certainly not a very humane one.

What priority then should be given to the impact hazard problem? Is it more important than all of these other hazards? Potentially, very large impacts, comparable to the late Cretaceous event, could result in massive global starvation. But such events have a mean frequency of once every 50 Myr. Smaller impacts may still result in sufficient climatic change to cause global crop failure and famines. If one uses the estimate of Toon et al. (this volume) then that threshold occurs for impacts of objects 1 to 2.2 km in diameter, or with frequencies of about once every  $1.1 \times 10^4$  to  $5 \times 10^5$  years.

Among the hazards listed above, only two likely have the potential for massive, near-term

loss of life on a global scale: nuclear war and AIDS. The threat of nuclear annihilation has decreased substantially in recent years as a result of the end of Cold War. However, many nations still possess nuclear weapons and others are attempting to obtain them. Some of the present or potential nuclear-capable nations are in what would be considered “trouble spots”, e.g., the Middle East, and so there is heightened potential for nuclear incidents, with unknown consequences.

The AIDS epidemic has now spread worldwide; an estimated 10 million people are infected with the AIDS virus including 2 million in the United States (Karplus 1992). AIDS related deaths in the United States averaged 15,700 yr<sup>-1</sup> from 1987-89 (Wright 1991). Intensive medical research efforts to develop a cure and/or a vaccine have so far only met with limited results. It is entirely possible that a solution may appear at any time, but at present the disease continues to spread at an alarming rate.

Each of these two hazards clearly demand immediate and substantial attention and resources. Each has received substantial resources, both in the United States and in other developed countries. Given the immediate nature of these threats, it is entirely logical that they have priority over the impact hazard.

The other hazards listed above fall into two groups: immediate problems that continue to result in high death rates, and long-range problems whose effects are small now but have the potential to become major calamities in the foreseeable future. Examples of the first type of hazard are malnutrition and disease; examples of the latter are global warming and overpopulation. Note that for these problems, the phrase “foreseeable future” refers to the next 50 to 100 years. This is a relatively short time span as compared with the frequencies derived earlier for impact events.

It is worthwhile to discuss one of the lesser hazards listed above in somewhat more detail. During this author's preparation for the Tucson Hazards meeting, an article appeared in the Los Angeles Times (December 17, 1992) describing the United Nation's efforts at dealing with common childhood diseases in underdeveloped countries. The article, shown in Figure 1, reported that approximately 2.1 million children would die in the coming year as a result of preventable childhood diseases, because of a lack of vaccination programs in the underdeveloped nations. An additional 6.6 million children will die of curable diseases such as pneumonia and diarrheal diseases. The estimate is necessarily statistical and based on past experience. However, the uncertainties in the estimate are likely relatively small, on the order of perhaps 10 to 20%. Thus, it is not a question of whether or not these children *may* die, but rather only the precise number that *will* die.

Annual death rates provide one basis for comparing the relative importance of individual hazards. Chapman and Morrison (1993) have estimated that the nominal threshold impactor that will cause sufficient global climatic disruption to result in starvation of  $10^9$  people, a 1.5 km diameter impactor, similar to the event discussed in the previous section, results in an *average* annual worldwide fatality rate of  $\sim 3,000 \text{ yr}^{-1}$ . The actual deaths likely all occur within one to two years after the impact, but the low expected frequency of the event results in the modest annual fatality rate. Thus, on the basis of annual fatalities, the impact hazard is orders of magnitude less lethal than the current lack of minimal medical programs for children in underdeveloped nations.

These figures can be compared with annual deaths in the United States from various other causes (data for 1987; Wright 1991): fires and burns, 5,000; drowning, 5,000; falls, 12,000; motor vehicle accidents, 46,000; homicide, 19,000; suicide, **30,000**; cancer, 473,000.

Thus, there area wide range of hazards, either natural or man-made, which are either comparable to or greatly exceed annual death rates expected from impacts. For each of these hazards there are oftentimes simple technological fixes which would contribute to greatly decreasing the death rates: e.g., mandatory seat belt laws for motorists; life jacket laws for boaters; smoke detectors in homes and workplaces. For others of these hazards, continued research can likely also improve death rates: e.g., cancer. In yet other cases, there are legal remedies which could have potentially very large effects: e.g., gun control to decrease homicide rates.

The point is that based on normal methods for evaluating risks such as annual fatality rates or frequency of occurrence, the impact hazard does not appear to have higher priority than many other problems with which society currently deals. Again, the problem here is how to respond to a very low probability event with a very high potential damage level.

What do public officials think of the impact hazard? In 1992, the Democratic vice-presidential candidate (and eventual winner), Senator Albert Gore Jr., published a book on environmental problems facing society, *Earth in the Balance* (1992). The book described a wide range of ecological problems, including overpopulation, ozone depletion, global warming, climate fluctuation (from volcanic dust input), and deforestation. No mention was made of the impact hazard, despite the fact that Senator Gore sat on the subcommittee that oversaw the NASA budget. The Senator (now Vice-President) either judged that the impact hazard was not significant enough to include, or that it was not a sufficiently credible threat.

Similarly, a recent book by W. J. Karplus with the intriguing title *The Heavens Are Falling: The Scientific Prediction of Catastrophes in Our Time* (1992) discusses eight major hazards facing society, including ozone depletion, climate change, overpopulation, AIDS and

earthquakes. The book does not mention the asteroid hazard.

Thus, the impact hazard is just one of a large number of problems currently facing society. If resources are spent to mitigate impacts on the Earth by large asteroids or comets, then they will likely come from resources currently spent on other, more immediate problems, at a likely cost of human lives. Deciding on what priority to give each individual hazard will continue to be a difficult process.

### **Credibility of the Impact Hazard**

The issue of credibility is a very important one for the impact hazard. As often noted, this topic has a high “giggle factor” and it is often not taken very seriously by the public or press. If an effective defense is to be developed against asteroid and comet impacts, then there must be widespread public understanding and support of the problem.

As noted in the introduction, public experience is that asteroids and comets do not strike the Earth; there is no known incident of a major cratering event in human history. As reporting of random meteorite falls like the 1992 Peekskill, NY event becomes more widespread, public opinion may begin to accept the idea of larger impacts being possible.

One problem for those advocating an impact hazard defense and/or detection system is that their recommendations often appear to be self-serving. Small-body astronomers have advocated a program of observing that emphasizes a search for large ( $> 1$  km) Earth-crossing asteroids and comets (Morrison 1992). These are, in general, the same objects that those astronomers are currently discovering with their existing search programs, and so their conclusions can be viewed as a means for simply obtaining additional funding and instrumentation. Similarly, recommendations by scientists and technologists involved with

deflection efforts have been to emphasize the danger of the smaller, Tunguska-like airburst events (Canavan et al. 1993). These smaller impactors are far more frequent, and thus more likely to create alarm. At the same time, they are small enough to be destroyed and/or deflected with currently existing technologies and warhead yields, similar in many ways to concepts studied for ballistic missile defense.

At first glance, the two groups can not both be right about which size range of objects poses the greatest hazard. A cynical observer would conclude that one or both groups is perhaps biasing its conclusions to fit its own needs. This perception of self-serving conclusions is further re-enforced by the declining funding situation at present for both planetary science and defense-related technology efforts in the United States and elsewhere. An example of this type of reaction by the media is shown in Figure 2.

However, a more careful examination is clearly required. Although the conclusions may appear self-serving, that does not stop them from being correct. A medical doctor will benefit financially from the illness of his patients, but that does not mean that he will deliberately make them ill, or that he will find illnesses to be treated when none in fact exist (in most cases). In addition, legitimate scientific analyses often disagree when there is a lack of definitive data, or when the parties to the debate come from different communities of scholars, with different training and different philosophical outlooks. The scientists and technologists best able to advise the public on the impact hazard and possible deflection techniques are necessarily those who are already expert in these fields. As knowledge of this problem matures, it is likely that agreement will be reached on more and more of the relevant issues.

The problem then is how to create an atmosphere of credibility for the impact hazard problem. The answer is to approach the problem slowly, and to conduct a patient campaign of

public education in this area, This will clearly take time, but if demands for resources are rushed before the public acceptance of impacts is firm, then it is more likely that resistance will form and will be difficult to overcome.

Consider how society has reacted to other new environmental hazards as they have been discovered. The ozone depletion problem due to chlorofluorocarbons was first introduced by Molina and Rowland in 1974. The idea initially received a great deal of attention and public debate, and many of the reactions to it were openly hostile. Because the problem involved what was then an \$8 billion industry in the United States, manufacturers of chlorofluorocarbons were particularly anxious to refute Molina and Rowland's conclusions (Ehrlich and Ehrlich 1989). At one point, a leading industrial journal went so far as to charge that the ozone problem was a KGB plot to destabilize Western industry.

Support for the ozone problem oscillated back and forth for over a decade until the discovery of the Antarctic ozone hole in 1985. At that point the weight of evidence became great enough to force worldwide action on the problem, though even then there still was much resistance and foot-dragging because of the economic issues involved (Ehrlich and Ehrlich 1989).

Similar conclusions can be drawn from looking at initial public reaction to questions raised over pesticides, acid rain, global warming, etc. New scientific or technological problems are greeted with curiosity and interest, but resistance often builds because of vested interests that may be threatened by the solution. If the evidence is not overwhelming then it will be debated and a range of conclusions will be drawn, which usually extends from "no problem" to "immediate crisis." Additional data must be accumulated to resolve these questions. At the same time, the public, including the press and government decision makers, must be educated as to the nature of each problem.

The impact hazard problem is still a very immature one, in that the public education process has only just begun. Before public opinion will support the use of substantial government resources, i.e., tax dollars, to developing an asteroid and comet defense, it must first be convinced that the threat is genuine. That convincing will take time,

### **Other Issues: Plausibility, Legality, and Safety**

**Plausibility:** Current expectations about the technology necessary to deflect asteroids and comets have centered around the use of nuclear weapons, launched on conventional rockets. Clearly, some form of rudimentary defense system could be constructed against potential impactors, particularly the smaller objects, using this technology. But will such a defensive system work? As argued above, the current state of knowledge of comet and asteroid internal structure and regoliths is not sufficient to accurately predict the effects of a deflecting blast. In particular, the likely rubble pile nature of asteroids and cometary nuclei raises the threat that much of the energy will be expended disrupting the object rather than deflecting it. The consequences of disruption could well be to increase the lethal effects of the impactor(s).

The studies of possible deflection technologies to date (e.g., Canavan et al. 1993) are still fairly modest, and have not yet considered the problem in the detail necessary to know how well such a system would work. Before one goes forward with an actual hardware program, these studies need to be performed at a far more detailed level, and covering the full range of possible asteroid and comet parameters (unless better data becomes available). In addition, all aspects of a defensive system must be considered, not just the deflecting rockets, but the detection system that will find potential impactors as well. The current Spaceguard proposal (Morrison 1992) outlines plans for a system that will detect the  $> 1$  km objects and some fraction of the

smaller objects. If the decision is taken to try and defend against smaller objects, then a far more comprehensive detection system must be developed, and the costs and relative merits of such a system must be weighed very carefully.

One should also consider the possible role of emerging technologies in developing an effective impactor defense. Just because one can build a defensive system with the technology now in hand, does not mean that a defense should be built. It is highly possible that new technologies that are currently not anticipated will provide breakthroughs that make development of an impactor defense far easier and cheaper. Predicting what those technologies will be is probably a futile exercise, but there is certainly potential for very large advances in the near future in superconductivity, artificial intelligence, and miniaturization of electronics. The point is that one cannot say what new and useful technologies will be available in 20 or 50 years, yet there certainly are going to be some, and that is a very short time to wait relative to the time scale of the impact hazard.

**Legality:** The 1967 Outer Space Treaty bans the use of nuclear weapons in space (Florini 1985). Specifically, the treaty says,

“States Parties to the Treaty undertake not to place in orbit around the earth any objects carrying nuclear weapons or any other kinds of weapons of mass destruction, install such weapons on celestial bodies, or station such weapons in outer space in any other manner.”

Use or testing of nuclear weapons in space is also banned by the 1963 Treaty Banning Nuclear Weapons Test in the Atmosphere, in Outer Space, and Under Water.

Development of an asteroid/comet defense, as currently envisioned, would violate these treaties because of the use of nuclear weapons to provide the deflection impulse. It should, of course, be possible to negotiate exceptions to the treaties so as make a planetary defense system legal under international law. However, such negotiations should not be entered into lightly,

since the treaties provide valuable safeguards which make nuclear war less likely.

Any weapon that could be used to deflect asteroids could obviously also be used directly against nations on the Earth. As the world powers continue to “build down” nuclear weapons systems, individual nations will require assurances of their own security before they agree to give up their weapons. The development of any nuclear defensive capability against impactors will have to be accomplished under international scrutiny and will have to provide sufficient safeguards against malicious use, including against possible terrorist actions.

**Safety:** Ultimately, one of the important goals of any impact hazard defense must be that it is safe to use, and that it does not pose a greater threat than the impact hazard itself. In fact, given that the possible global damage from the larger impacts is so great, the potential threat from the defensive system must be far less.

The section above has mentioned some political concerns associated with the safety of a standby defensive system. Other concerns would be the safe and successful launch of the large warheads (a problem presumably already solved by nuclear weapons designers), and the subsequent orbital evolution of a deflected or disrupted comet or asteroid. If a threatening impactor is disrupted then, since its debris will all still be in an Earth-approaching orbit, the larger chunks will need to be tracked and have their orbits predicted well into the future.

If a defensive system is developed, there will naturally be a desire to test it. That test must be performed in a dynamically safe area of the solar system, well away from the Earth. If the test is done on actual near-Earth objects, then there is a potential for accidentally deflecting an object onto an impacting trajectory, should the test go awry. Tests should be performed on analog objects in the mainbelt, and well away from the dynamical and secular resonances that deliver objects into Earth-crossing orbits.

## **Discussion**

There is no doubt that impacts of comets and asteroids pose a genuine threat to human life on the Earth, with possibly extremely lethal consequences. There is also no doubt that impacts are only one of a large number of environmental threats that are currently recognized and which society must consider. None of the problems can be ignored, and none of the problems can consume all of the resources available to deal with them.

The story of “Chicken-Little” is firmly entrenched in the public consciousness. That story unfortunately creates a negative reaction to claims of impending disaster as a result of comet and asteroid impacts. In addition, common experience says that such events are not very likely, if they occur at all.

As scientists we know that they do occur, and that they have occurred on Earth with devastating consequences. Scientific investigations of past impact events, such as the late Cretaceous extinction, have tended to focus on the largest and most destructive events. This creates an unconscious bias within the scientific community that any future events will have similar consequences. That is certainly true for some, very rare events. The question we can not presently answer is at what level do smaller, more frequent impact events still have globally catastrophic consequences?

In addition, catastrophic events that occur frequently on the astronomical or geological time scales with which we are used to dealing, have a very low probability on human time scales. Again, this difference in perception heightens the concern of the scientists relative to that experienced by the general public.

Furthermore, there is a very different perception among the public with regard to natural

and man-made disasters. On the assumption that human beings have some control over their technological creations, systems such as air travel, nuclear power, and food production are required to have very high safety standards. This is particularly true in instances where humans must surrender their control to others; deaths in air travel are investigated intensely, while a much higher annual death rate from motor vehicle accidents is accepted with far less questioning. In contrast, humans regularly decide to accept the risk of living in earthquake zones, on flood plains, or in areas frequented by tornados or hurricanes, either because the frequency of such catastrophes is not high enough to evoke concern, or because of overriding economic and social requirements, or because they are viewed as natural disasters, and thus, “nobody’s fault. ”

As a natural disaster, and a very infrequent one, the impact of comets and asteroids is less likely to evoke concern than ozone depletion or global warming, because the latter are looked upon as man-made disasters, and the likely time scale for those problems to become serious is far shorter. This ignores an important fact about the impact hazard, that it is random and could occur at any time, but that too is part of the nature of the human response to hazards.

Lastly, a significant problem is what might be termed the “gender gap” of the impact hazard. During the Tucson meeting a woman astronomer attending some of the sessions commented to friends on what she perceived as the “little boys and their bombs” aspect of the ongoing studies. It is a fact that the vast majority of scientists involved in this problem are male: the Morrison (1992) report, for example, was authored by 22 men and 2 women, and reviewed by 4 men; the senior authors of the Canavan et al. (1993) report were all men. This is out of proportion to the ratio of men to women in planetary astronomy and in defense technology. It is entirely possible that one-half of the Earth’s population may regard the

attention given the impact hazard as an unnecessary exercise.

This paper has attempted to show that rapid action in developing an asteroid and comet defense is neither necessary, nor prudent. Expected frequencies of impacts are low compared to other natural disasters and it is unlikely that waiting a modest period of time to start a technological program will substantially endanger human beings on this planet. The current state of knowledge of the physical nature of asteroids and comets is not sufficient to design a deflection defense at this time. There exist a large number of other problems facing society which are more immediate in nature, and which threaten far higher annual fatality rates. The current public acceptance of the reality of the impact hazard is poor and there exists a genuine need for a program of public education before governments can be convinced to devote substantial resources to this problem. Lastly, a variety of technological, legal, and safety issues must be solved before development of an asteroid and comet defense can go forward.

At the present time, the best advice that I can offer to my scientific and technological colleagues is, "Go slow, " Premature or overly ambitious attempts to divert substantial resources to dealing with the impact hazard are likely to have negative results. The correct course is to carefully prepare the public for the problem by a program of public education, along with ongoing observational studies to find potential impactors and to improve our knowledge of asteroids and comets. Since many of the important questions can only be answered by direct, *in situ* measurements, a program of spacecraft rendezvous missions is called for, to as large and diverse a number of these objects as possible,

This paper has likely raised more questions than it has answered. In general, these are political, social and moral issues which need to be debated openly by all concerned parties. One wishes for the wisdom of Solomon to provide the answers, The decisions that need to be made

will not be easy, nor will the patience that must be exercised in educating the public while building the case for action on the impact hazard problem. As scientists, our task will be to increase our understanding of the hazard, inform the public and government as to what we have learned, and recommend prudent courses of action. It is a heavy responsibility, and one that no scientist involved in this area should take lightly.

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## Figure Captions

Figure 1. Front page article from the Los Angeles Times, December 17, 1992, describing statistics of child fatalities in underdeveloped countries due to a lack of basic medical treatments and vaccination programs.

Figure 2. One political cartoonist's view of the danger posed by asteroid and comet impacts, and the response to that danger by members of the Strategic Defense Initiative.

# U.N. Calls Many Child Deaths Preventable

By ANNE C. ROARK  
TIMES STAFF WRITER

Pneumonia is now the biggest killer of children in the world, resulting in 3.6 million deaths annually, but in most cases the cure is a five-day course of antibiotics that costs only 25 cents, according to a United Nations report released today.

The means of stopping pneumonia and dozens of other childhood diseases are now "available and affordable," the report said, but countries are not making the necessary investments in basic medical care, sanitation and education.

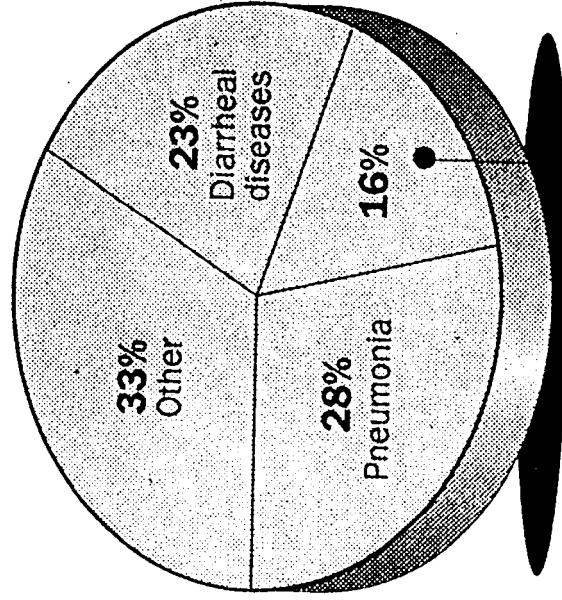
"The present neglect," the report said, "is a scandal of which the public is largely unaware."

Each week, the report found, a quarter of a million children die of malnutrition and diseases that are either curable or preventable.

"No famine, no flood, no earthquake, no war has ever claimed the lives of 250,000 children each year."

## Child Deaths

*More than 65% of the 12.9 million child deaths in the world each year are caused by pneumonia, diarrheal diseases, vaccine-preventable diseases or some combination of the three. Here are the main causes of deaths under age 5 in developing countries in 1990.*



Vaccine-preventable diseases

Measles: 880,000  
Whooping cough: 360,000  
Tuberculosis: 300,000  
Neonatal tetanus: 560,000

Source: WHO and UNICEF

PATRICIA MITCHELL / Los

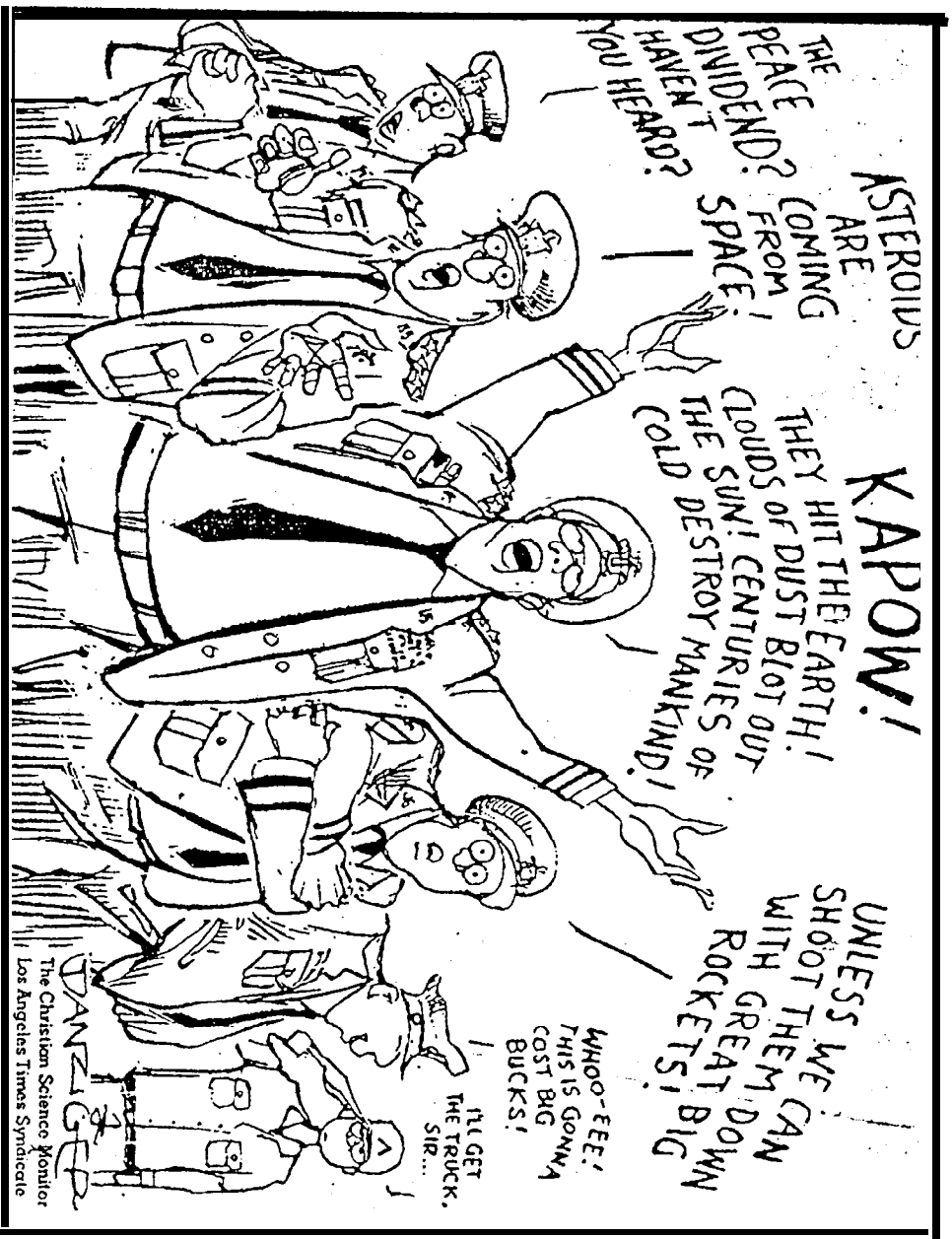


Figure 2.